

A new deep-depletion CCD for the red channel of the Palomar Double Spectrograph

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ABSTRACT

The red channel of the Palomar Double Spectrograph (DBSP) on the 200-inch Hale Telescope has been upgraded with a new deep-depletion CCD from LBNL. Its redder response produced a significant increase of the throughput above 550 nm, and its longer dimension more than doubled the spectral coverage. A special Dewar was designed to accommodate a detector mount which includes features to minimize CCD motion due to thermal cycling, in spite of the very simple "picture frame" packaging of the CCD. The new Dewar also includes some novel features to improve the liquid nitrogen hold time while staying within the size envelope allowed in the Cassegrain cage. We describe these changes along with the detector characterization.

Keywords: CCD, deep-depletion, spectrograph.

1. INTRODUCTION

The Palomar Double Spectrograph (DBSP) is a low- to moderate-resolution spectrograph [1] originally built in 1982 for the Cassegrain focus of the 200-inch Hale telescope on Mount Palomar. It has two channels, red and blue, separated by a dichroic filter, which can be used simultaneously to cover from 320 nm to beyond 1 μ m. Each channel has its own camera and detector system, which are electrically independent, and can be operated in synchronized or unsynchronized mode.

The red channel spectral coverage is from 550 nm to 1030 nm.

An overview of the Red channel optics is shown in Fig. 1.

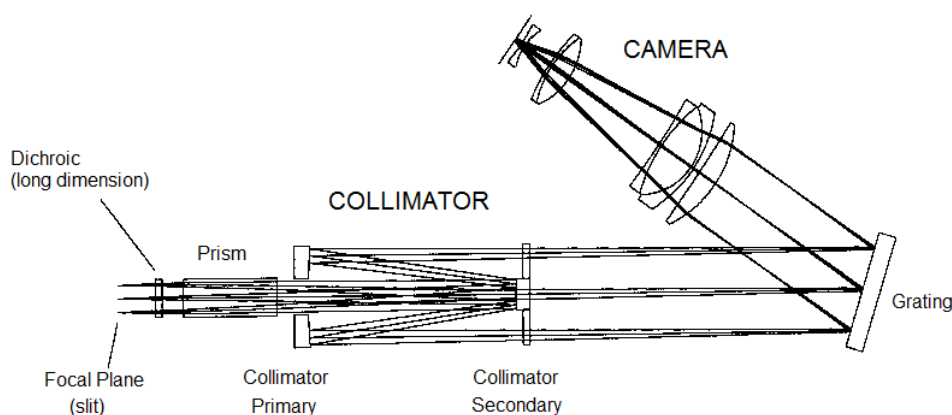


Figure 1: Overview of the optical path for the Red channel of DBSP.

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The cameras on both channels have been upgraded several times in the past, with the blue channel having had the most changes, the latest being the installation of a thinned, anti-reflection-coated E2V 4096×2048 CCD in 2005, which is the one currently in operation. The first modification to the red channel occurred in 1995, when the original camera between the collimator and the detector was replaced with a seven-element design by Harland Epps of the University of California/Lick Observatories, and the original Texas Instruments 800×800 CCD was replaced with a thinned, anti-reflection-coated Tektronix 1024×1024 CCD. That was the detector in use until this upgrade.

The new detector is a 4114×2040 CCD, manufactured and packaged at Lawrence Berkeley National Laboratories (LBNL). It is a p-channel back-illuminated CCD with serial registers on the long sides of the CCD, $250 \mu\text{m}$ thick and fully depleted [2]. The pixel size is 15 microns.

A summary of the main characteristics of the new CCD compared to the previous one is presented in Table 1.

Table 1. CCD characteristics for the Red channel of DBSP, before and after the upgrade.

Characteristic	Before	After
First Light	1995	2011
Manufacturer	Tektronix	LBNL
CCD Format (pixels)	1024×1024	4114×2040
Pixel size (μm)	24	15
Plate scale (arcsec/pixel)	0.468	0.293
Max spectral length (mm)	24.6	61.7

2. MECHANICAL DESIGN

2.1 Detector Mount

With the goal of keeping the CCD in place during cool-down in spite of differential thermal contraction, the detector mount defines axial position, tip and tilt with three reference landing pads contacting the back of the Aluminum Nitride (AlN) package. The picture frame package of the CCD was held to the mount with “spring leaves” acting through stacked layers of the fiberglass and AlN backing plate which easily tolerate the forces necessary to hold the CCD under gravity and impact loads during shipping. Lateral position is defined by a circular pin making a snug fit into an existing hole at one corner of the fiberglass “picture frame” to which the CCD is wire bonded. Rotation is defined by another pin fitting snugly into a second hole in the detector package. To avoid modifying the detector package, a flexure was machined into the pin to allow contraction and manufacturing tolerances along the line between the two pins. Fig. 2 shows a model of the final design (a) and a picture of the completed assembly with the CCD in place (b).

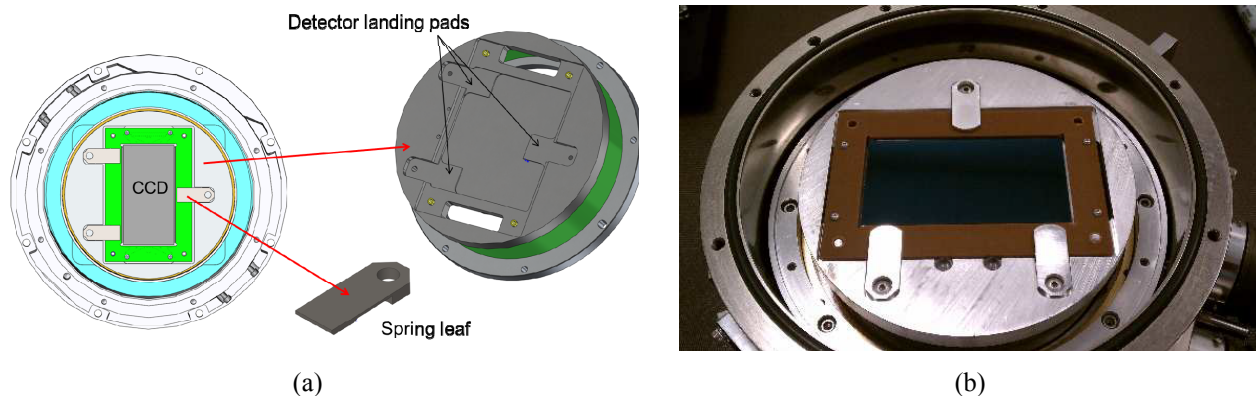


Figure 2: (a) Model of the detector mount. (b) The assembly as built with CCD installed.

The vertical position of the landing pads was verified using an optical profilometer, taking as a reference surface the flange that connects to the camera body.

For temperature regulation, the detector mount includes a resistive temperature sensor and a chain of resistors distributing heat fairly uniformly across the detector support plate. The control loop is managed by a Model 340 Lakeshore temperature controller. The set-point established for this application was 118K.

2.2 Dewar

The Dewar fabrication was contracted with Infrared Laboratories Inc., of Tucson, Arizona. Using their standard ND-5 model as a starting design, several custom modifications were requested with the ultimate goal of increasing the LN2 hold-time for most gravity orientations while staying within the allowable volume envelope given by the location of the camera within the instrument.

The main custom modifications requested were:

- Shorter fill tube to and increased vessel volume (20%).
- LN2 filling port offset from the center (optimized to increase the volume of LN2 while minimizing spillage).
- Provision to install an over-sized activated charcoal getter container attached to top of tank.

The activated charcoal container is mounted directly onto the LN2 vessel, as its cryo-pumping efficiency is best at low temperatures. In addition a Zeolite desiccant container is attached to the external wall of the Dewar (i.e. at room temperature) where it can be charged with fresh Zeolite as needed, without opening the Dewar.

Our calculations gave a hold time of over 30 hours, allowing for one daily LN2 refill instead of the previous twice-a-day schedule, easing summit operations.

2.3 Dewar window

The Dewar window is a bi-convex field flattener. We used the original prescription for the Epps camera, but increased the diameter it for a wider field. A model of the window mounted on its flange is shown in Fig. 3.

An FEA study was performed to ensure that the bigger window would not fail mechanically. In the study atmospheric pressure was applied on the exposed lens surface while the opposite side rested on its flange. The safety factor was found to be 4, assuming a maximum allowable stress of 500 psi.

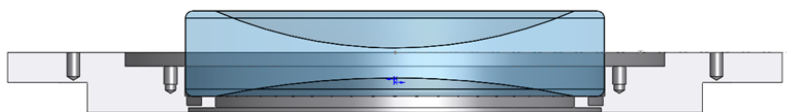


Figure 3: Model of the Dewar window mounted on its flange.

2.4 Radiation shield

Careful design of the radiation shield around the detector mount was the largest contributor to improved hold time. Cracks and openings for cable feed-through were minimized since they have unit emissivity, although the opposing Dewar wall was polished for moderately low emissivity. The mask between the CCD and the Dewar window (Fig. 4) is particularly critical since both the CCD and the fused silica window have unit emissivity at $10\mu\text{m}$ where the room temperature black body curve peaks. The mating of the radiation shield around the detector mount to the gas cooled shield around the LN2 vessel was via a concentric circle of spring fingers to allow easy disconnection of the two shields while providing enough contact surface and force when inserted, while accommodating moderate misalignments.



Figure 4: View of the gold plated cold mask on top of the CCD.

3. DETECTOR CHARACTERIZATION

3.1 CCD description

The detector was manufactured and packaged at Lawrence Berkeley National Laboratories (LBNL). The 4114×2040 pixel p-channel CCD is back-illuminated CCD and fully depleted throughout its $250\ \mu\text{m}$ thickness by a 60V positive bias applied to the transparent conductive Indium Tin Oxide layer which also serves as a layer in the anti-reflection coating [2]. The thickness offers excellent sensitivity in the far red and virtually eliminates fringing while the lateral charge diffusion remains small compared to the $15\ \mu\text{m}$ pixel and insignificant compared to the typical 2.5 pixel ($37.5\ \mu\text{m}$) spectral line width (FWHM). These characteristics were the main motivation for using the device for this upgrade. The device is identical to the two CCDs used in the SWIFT spectrograph built by Oxford University for use at Palomar Observatory [3].

Serial registers run along the long side with output amplifiers at each corner, supporting efficient binning of spectral in the spatial direction, while also minimizing readout time for high aspect ratio regions of interest needed for spectroscopy. There are 7 extended pixels on each side of the serial registers. These pre-scan pixels allows for settling of the line start transient prior to accessing the image area. The imaging area is split top and bottom into two parallel registers, which are in turn split into image areas and storage areas. However for this application, readout is typically through a single output, selected for lowest noise. The layout for one of the serial shift registers is shown in Fig. 5.

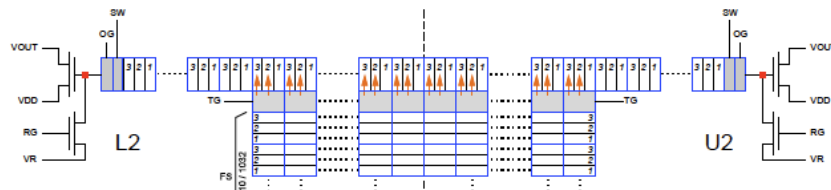


Figure 5: View of the geometry of one of the serial shift registers of the CCD.

The mask on top of the CCD limits the exposed area to the region where the spectrum is delivered by the camera optics. Therefore the CCD is always operated in “Region-Of-Interest” (ROI) mode (also known as “window mode”) in the vertical direction only (effectively a “Band-Of-Interest”), where rows are skipped at the beginning and at the end of the full readout. For this instrument, only 440 rows are read, from row 790 to 1229 as shown in Fig. 6.

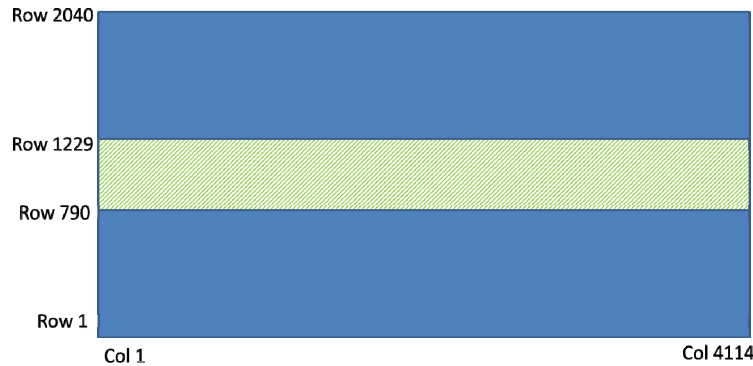


Figure 6: Diagram of the “Band-Of-Interest” used for the instrument operation, between rows 790 and 1129.

To avoid the middle section discontinuity when using two or four amplifiers, the device is operated in single-amplifier mode. The amplifier selected was U1, based on its noise performance. All the results presented below correspond to this amplifier.

The use of a high substrate bias voltage, +60V to achieve full depletion, required a dedicated high voltage bias generator in the detector readout electronics, implemented on a dedicated board designed by LBNL and manufactured by Astronomical Research Cameras Inc. (ARC). Input and output voltages for the p-channel CCD are inverted with respect to typical (n-channel) CCDs.

The p-channel CCD requires two readout procedures that are unique to this type of CCD:

1. a special erase procedure eliminates residual images (caused by the emptying of dielectric interface traps at the Si/SiO₂ interface by the excess hole carriers produced by saturation), and
2. an e-purge procedure to avoid images that can have irregular baselines and a very noisy (fixed pattern) appearance, produced by the lack of a structure interconnecting the channel stop implants, causing the individual channel stops to become isolated. In this case it is possible for the channel stops to be left in different charged states after a low temperature power-up or an erase procedure [4].

The special erase procedure consists in ramping down the substrate voltage bias (V_{sub}) to 0V, then increasing the parallel clocks to a high value to produce inversion, and after a brief delay (500 ms), ramping V_{sub} back to its operating level (+60V). The parallel clocks are set to their normal values when V_{sub} reaches 10V.

The e-purge procedure consists in setting all the parallel clocks to -8V (strong accumulation potential) for 500 ms, without changing V_{sub} .

Both procedures are performed automatically before the beginning of an exposure, after the CCD has been idle.

3.2 Conversion Gain

The conversion gain was calculated using the standard photon transfer curve method, where pairs of nearly flat images are taken at different exposure times. The mean of the sum is then plotted versus the variance of the difference for every pair, over a specified region. Slope is at low to moderate intensities equal to the number of electrons per ADU.

The conversion gain was calculated for the three different electronic gain settings, with the following results (without the small correction for spatial correlation in the difference images reported by Downing [5]):

- Gain x1: Conversion gain = 5.9 e-/adu
- Gain x2: Conversion gain = 2.8 e-/adu
- Gain x4.75: Conversion gain = 1.2 e-/adu

The conversion gain of 2.8 e-/adu was selected as the default for the application, as a compromise between dynamic range and readout noise.

A plot of the photon transfer curve for the selected gain is shown in Fig. 7.

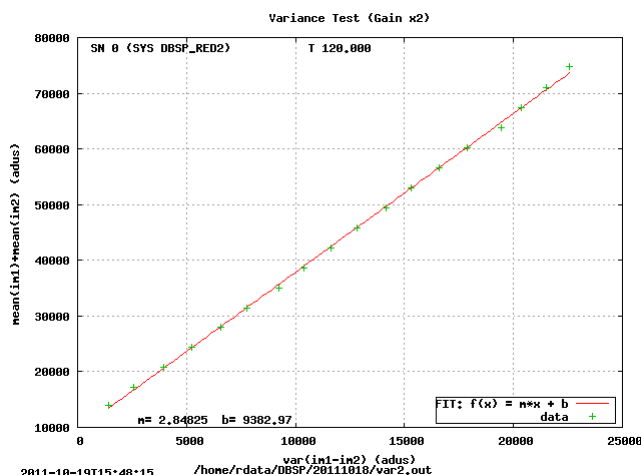


Figure 7: Photon transfer curve for the CCD with the settings used for the instrument operation.

3.3 Readout noise

The readout noise at the time of the release of the instrument was 8 e- RMS, much higher than our initial goal of 3 e- RMS. EMI shielding and ferrite core clamps were installed around the signal wires which helped lower the noise, but we could not lower it beyond 8 e- RMS. It was decided that the instrument would be released for science after identifying possible courses of action for future interventions: improvement of the EMI shielding on power cables and optimization of the detector waveforms to include longer settling time delays.

3.4 Full well

The saturation full well was found to be 110,000 e-. A saturation plot is shown in Fig. 8.

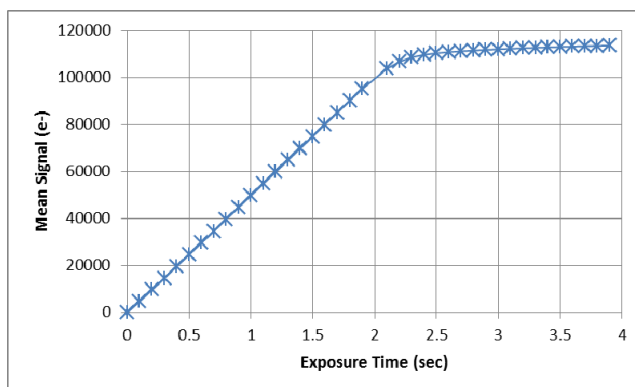


Figure 8: Saturation plot showing the full-well level at 110,000 e-.

3.5 Linearity

The linearity of the CCD was determined to be better than 1% up to 85,000 e⁻. A non-linearity plot is shown in Fig. 9.

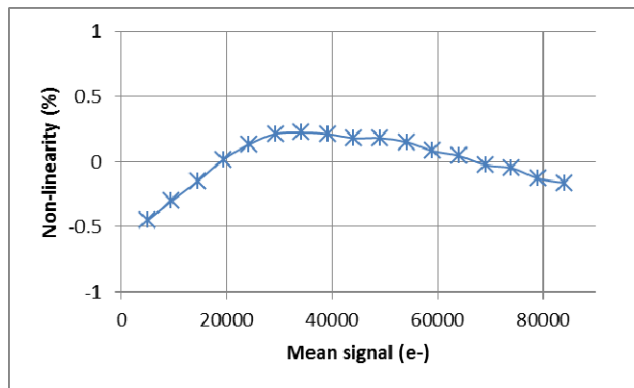


Figure 9: Non-linearity plot for the CCD, showing that it stays within a 1% band.

3.6 Dark current

The dark current was measured to be around 12 e⁻/pixel/hour at the operating temperature of 118K. A section of a 40-minute exposure image is presented in Fig. 10, showing trails from both cosmic rays and Compton electrons from local background radiation.

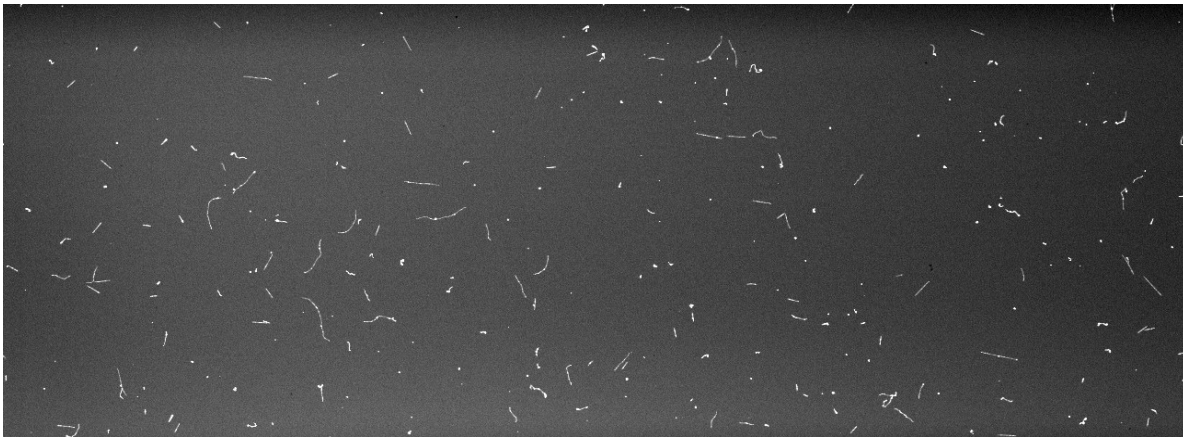


Figure 10: Section of a 40-minute exposure dark image.

4. READOUT ELECTRONICS AND SOFTWARE

4.1 Readout electronics

A conventional CCD controller from Astronomical Research Cameras Inc. (ARC) was able to accommodate the inverted polarity of the p-channel CCD signals, but was equipped with an additional board, also supplied by ARC to provide the high voltage backside bias (designed by LBNL), including the ability to ramp the voltage up and down at a specified rate.

The electronics remain mounted when the Dewar is removed from the instrument to protect the CCD from ESD hazards. Two panel connectors on the box mate directly to the 55-pin hermetic connectors so that there is no intermediate cable. The box is orientated so that the card extraction direction is orthogonal to the Dewar. The more natural parallel orientation (which minimizes wiring length to the CCD) results in card extraction being blocked by the instrument, which requires dismounting the camera, and was considered unacceptable for observatory operations.

The wiring path includes a patch panel which maps the controller pins to CCD pins. It is located underneath a cover on the exterior surface to allow easy access for probing any signal to or from the CCD, or for signal paths to be modified or opened. ESD sensitive pins are concealed under a second cover. Short cables with simple pin-to-pin mapping carry signals from the D connectors on the controller cards to the patch panel, where they can be disconnected and removed along with the card (Fig. 11). This simplifies the cable fabrication and allows the cards to be more easily extracted than would be possible if the cables remained in place.

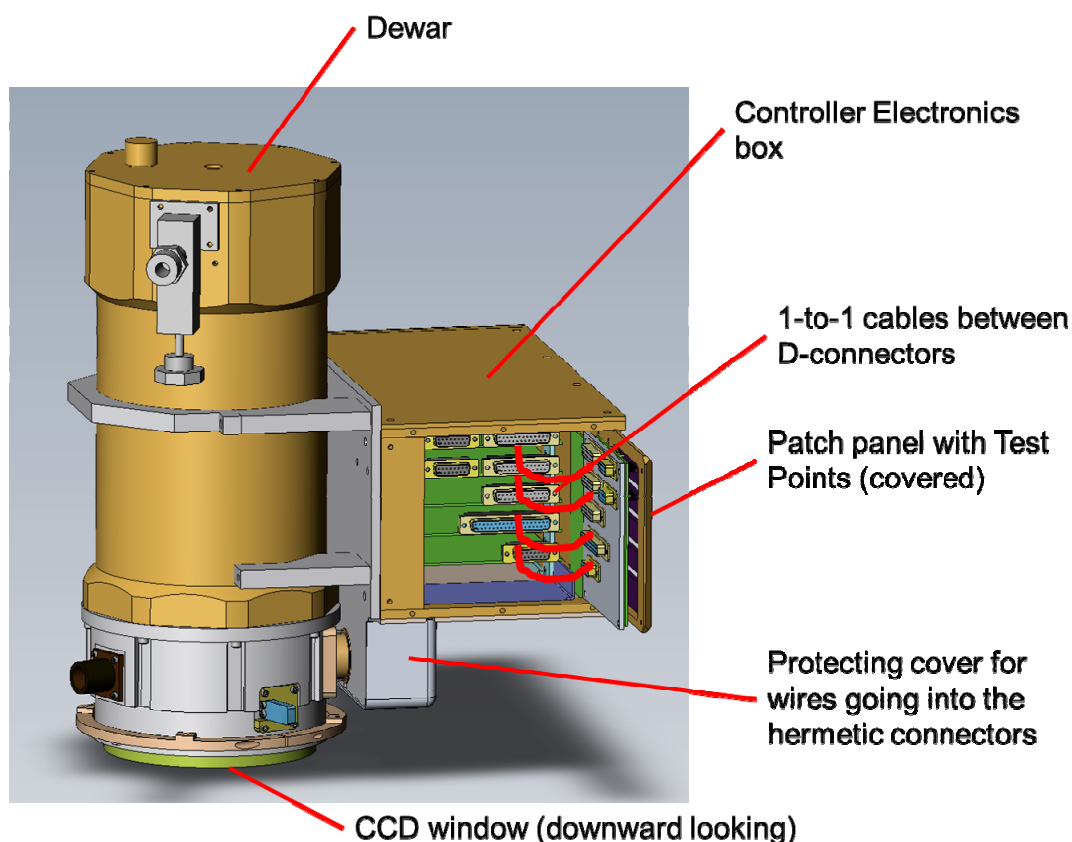


Figure 11: Model of the electronics box attached to the Dewar, showing the wiring setup designed to allow easy access to the boards and to test points of the CCD signals.

4.2 Software

For compatibility with the CCD on the blue side of the Double Spectrograph, the controller uses Palomar's in-house software package, ArcVIEW. A new software module was developed to optimize the focus procedure (still manual at this point), providing a large reduction in the time spent analyzing images to determine best focus.

5. FIRST ON-SKY RESULTS

First light for this upgrade was on October 27, 2011. The spectroscopic throughput of the new detector in comparison to its predecessor was calculated using the spectrophotometric standard star Feige 34 [6], as shown in Fig. 12. The black curve is from an observation on May 7, 2010 before the upgrade. The higher red curve is from October 30, 2011 after the upgrade. Dotted portions of the curve indicate interpolation over regions of strong molecular absorption from the terrestrial atmosphere.

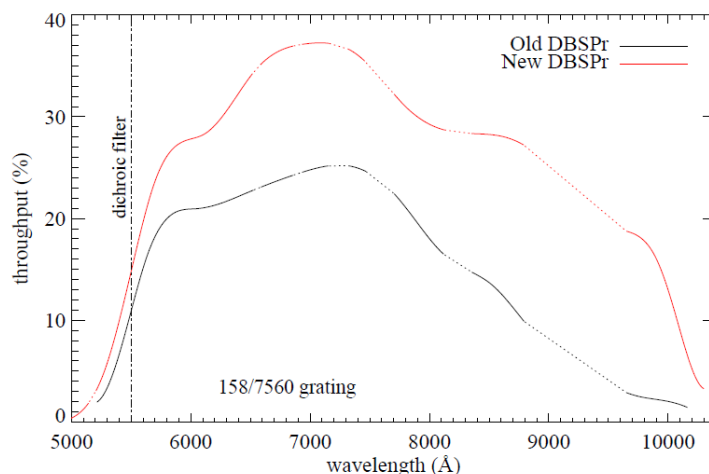


Figure 12: Spectroscopic throughput of the new red channel of DBSP with the 158 lines mm^{-1} grating with a blaze wavelength of 7560 Å. The losses from the atmosphere and the primary and secondary telescope mirrors have been removed.

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